Stratocumulus

Outline

1. Climatology: What they are, where and under what conditions they form, how they influence the climate system.
2. A description of the biases in their representation in large scale and coupled (atmosphere/ocean) climate models
3. Physics: Theoretical frameworks and understanding of processes influencing stratocumulus formation, maintenance and desiccation.
4. Perspectives on modeling stratocumulus as part of the climate system, and assessing their influence on climate change.

Concepts

- Cloud radiative effects
- Conserved (thermodynamic) variables
- Bulk models
- Ekman transport and upwelling

Reading

I recommend reading the papers by Stevens (2005), Klein and Hartmann (1993), Richter (2015) and Hourdin et al. (2015).

An overview that touches on many of the ideas presented in the class is that by Stevens (2005). A more comprehensive overview is presented by Wood (2012) with a good introduction into the literature up until that time. Lilly (1968); Schubert et al. (1979) and Randall (1980) are classic papers on the topic. The book chapter by de Roode and Neggers (2019) is a self contained presentation of much of the literature, albeit mostly focusing on models and conceptualisations of stratocumulus. The stratocumulus problem from the point of the view of the climate system is revised concisely by Richter (2015). Important papers on the topic, from the large scale perspective are Nigam (1997) and Klein and Hartmann (1993), for modelling studies see Ma et al. (1996) and Hourdin et al. (2015).

Exercises

These are not easy exercises, and I don't expect everyone to solve every problem. In attempting to solve them you may need to make assumptions, please feel free to do so. And if you don't know how to solve a problem think at least about a strategy for approaching a solution and outline that.

1. The radiative forcing from a doubling of atmospheric CO_2 is estimated to $3.7\,\mathrm{W\,m^{-2}}$. How much would the coverage of stratocumulus over the ocean have to decrease to have the same radiative forcing. Assume that the radiative forcing for the average stratocumulus is $-75\,\mathrm{W\,m^{-2}}$ and use the cloud coverage estimates from Wood (2012).

2. Some simple rules of thumb are helpful for understanding how clouds influence climate. One is that the albedo, α, can be expressed as

$$\alpha = \frac{\tau}{\tau + 7} \tag{1}$$

where τ is the cloud optical depth. The optical depth can, in turn, be related to the liquid water path (LWP) in units of $\mathrm{g\,m^{-2}}$ as

$$\tau = \frac{3}{2}\frac{\mathrm{LWP}}{\rho r_\mathrm{e}} \tag{2}$$

where ρ is the air density, which for low lying clouds is approximately unity, and r_e is the effective radius of cloud drops, in microns. A typical value would be $10\,\mathrm{\mu m}$ to $20\,\mathrm{\mu m}$, somewhat larger for more condensate laden clouds. Using these rules of thumb estimate the liquid water path of a cloud for it to have a short-wave radiative forcing of $-75\,\mathrm{W\,m^{-2}}$, and assuming that it forms over a black surface in an atmosphere otherwise transparent to visible radiation.

3. Can you estimate how your answer depends on surface albedo, i.e., what happens if the surface albedo is $10\,\%$, or $30\,\%$. Does the absorption of solar radiation by water vapor in and below the cloud influence the answer? If so how?

4. For a well mixed boundary layer some rules of thumb can help you relate the cloud base height (equivalently the lifting condensation level) to the surface relative humidity. From Lawrence (2005) one can estimate that cloud base (or the LCL) is given as $z_\mathrm{LCL} = 125(T - T_\mathrm{d})$ where T is the surface air-temperature and T_d the surface dew-point temperature. This 'dew-point' depression can be related to the surface relative humidity as $\mathrm{RH} = 100 - 5(T - T_\mathrm{d})$. Based on these rough formulae, and assuming that the surface flux is proportional to $(1 - \mathrm{RH})$ can you estimate how the surface latent heat flux changes if cloud-base increases from $200\,\mathrm{m}$ to $400\,\mathrm{m}$? How does this compare to the change from a cloud whose LWP is $60\,\mathrm{g\,m^{-2}}$ doubling in thickness?

5. How does cloud thickness depend on entrainment?

6. If cloud-top cooling doubles and entrainment rates do not change, can you calculate what would happen to the equilibrium cloud base height predicted by a mixed-layer model without horizontal advection? How would horizontal advection change the answer?

7. If radiative cooling is balanced by subsidence warming, what is the magnitude of the subsidence required to balance a cooling rate of $1\,\mathrm{K\,d^{-1}}$? Assuming a typical wind-speed of $7\,\mathrm{m\,s^{-1}}$ what gradient of cloud top height implies an equivalent subsidence velocity from horizontal advection.

8. Would you expect near surface winds to increase or decrease with increasing cloud? Why?

References

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